Appendix 10.4

Energy Isles Wind Farm, Shetland Islands

Peat Landslide Hazard and Risk Assessment

April 2019

Client	Energy Isles Ltd
Document Number	18-FEC-002-01
Author(s)	Andy Mills, Director
Approved by	David Rushton, Director
Version	01
Date	09/04/2019

evaluate
problem-solve
guide

Contents

1. INTRODUCTION

1.1. Background

1.1.1 Energy Isles Limited (the Applicant) are seeking consent under Section 36 of the Electricity Act 1989 for construction of the Energy Isles Wind Farm, Shetland (hereafter the 'Proposed Development'). The Proposed Development lies to the south and west of Gloup and is approximately 16.8km^2 (c. 1,679ha) in area. The site is relatively remote, with no major or minor transport routes within the site boundary.

1.1.2 The Proposed Development will comprise:

- 29 wind turbines with a maximum tip height of 200m, each with an associated transformer.
- A crane hardstanding area and blade laydown areas at each turbine location.
- A substation and control building.
- A network of buried electrical, telecommunications and control cables linking the substation/control building and turbines.
- 4 onsite temporary construction compounds.
- Up to 9 temporary borrow pits for the extraction of stone.
- A network of access tracks (18,35km floated, 0.98km temporary floated and restored and 1.75km of excavated) and turning areas linking the turbines and the substation/ control building;
- Widening of 0.523km of the Dalsetter Hill Road (known locally as the Old Cullivoe Road) which links the new access tracks to the A968.

1.1.3 The Scottish Government Best Practice Guidance (BPG) provides a screening tool to determine whether a peat landslide hazard and risk assessment (PLHRA) is required (Scottish Government, 2017). This is in the form of a flowchart, which indicates that where blanket peat is present, slopes exceed 2° and proposed infrastructure is located on peat, a PLHRA should be prepared. This conditions exist at the Proposed Development site and therefore a PLHRA is required.

1.2. Scope of Work

1.2.1 The scope of the PLHRA is as follows:

- Characterise the peatland geomorphology to determine whether prior incidences of instability have occurred and whether contributory factors that might lead to instability in future are present across the site.
- Determine the likelihood of a future peat landslide under natural conditions and in association with construction activities associated with the Proposed Development.
- Identify potential receptors that might be affected by peat landslides, should they occur, and quantify the associated risks.
- Provide appropriate mitigation and control measures to reduce risks to acceptable levels such that the Proposed Development is developed safely and with minimal risks to the environment.

1.2.2 The contents of this PLHRA have been prepared in accordance with the BPG, noting that the guidance "*should not be taken as prescriptive or used as a substitute for the developer's [consultant's] preferred methodology*" (Scottish Government, 2017).

1.3. Report Structure

1.3.1 This report is structured as follows:

- Section 2 provides a site description based on desk study and site observations, including consideration of aerial imagery, digital elevation data, geology and peat depth data.
- Section 3 gives context to the landslide risk assessment methodology through an account of peat landslide types and contributory factors before providing an overview of the approach taken for the Proposed Development.
- Section 4 describes the approach to and results of an assessment of peat landslide likelihood under both natural conditions and in association with construction of the Proposed Development.
- Section 5 describes the approach to and results of a consequence assessment that determines potential impacts on site receptors and the associated calculated risks.
- Section 6 provides mitigation and control measures to reduce or minimise these risks prior to, during and after construction.

1.3.2 Assessments within the PLHRA have been undertaken alongside assessments for the Peat Management Plan (Appendix 10.3). Where relevant information is available elsewhere in the Environmental Impact Assessment Report (EIA Report), this is referenced in the text rather than repeated in this report.

2. DESK STUDY

2.1. Topography

2.1.1 The Proposed Development site is located on gentle rolling hills of low relief. Elevations range between 112m (Sandwater Hill) and sea-level (Figure 1), with several low summits of around 100m elevation. Northern summits include the Hill of Vigon and Hill of Bakkanalee to the west of the Gloup Voe inlet and Sandwater Hill to the east. The central part of the site runs over undulating terrain from the Hill of Markamouth in the west to Muckle Bratt-houl in the east via Tonga Field. Fugla Field lies is the southernmost summit, falling gently to Gossa Water to the south.

2.1.2 Hillsides are generally slightly convex or rectilinear with the exception of the steep hillsides above Gloup Voe. Slope angles are generally low, typically <5° on summits to <10° on most hillsides. Exceptions are localised areas of steep slopes associated with watercourses, the steep northern hillsides of the Hill of Vigon in the north and the hillsides over Gossa Water and associated with its primary tributaries (Figure 2).

2.2. Geology

2.2.1 1:50,000 scale geological mapping shows the majority of the site to be overlain by peat with undifferentiated glacial till and morainic deposits at the margins of the site bordering the coastline and along the steep hillsides above Gloup Voe (Figure 3). Pockets of glaciofluvial deposits are scattered around the coastline and hummocky glacial deposits (diamictons of sand and gravel) are present on Sandwater Hill.

2.2.2 The Yell Sound division underlies the central part of the site, comprising Psammite across the hills and Psammite and Gneissose or Gneiss around the margins. Gneissose Pelite and Quartzite or Psammite and Gneissose are present on Sandwater Hill. Their metamorphic character indicates low permeability and has contributed to the conditions required for deep peat formation at the site.

2.2.3 The Carbon and Peatland map carbon-rich soils layer for Scotland shows the majority of the application site to be underlain by Class 1 or Class 2 soils, indicating that the soils on site regarded as nationally important carbon-rich soils, deep peat and priority peatland habitats either with high conservation value, or where degraded, with restoration potential.

2.3. Hydrology

2.3.1 There are two major catchments within the site, one occupying much of the southern half and draining to the Burn of Gossawater in the south and the other occupying the east and draining to Gloup Voe in the north. The western part of the Burn of Gossawater catchment also acts as the drinking water catchment for Gossa Water (Figure 4). In the north and west of the site, smaller catchments drain out to sea via a number of watercourses. The Hill of Vigon in the northwest of the site is drained to the north by the North and South Burns of Vigon and in the east by the Burn of Riggadale. The Hill of Markamouth in the mid-west of the site is drained to the west by the Burns of Midge Glen and Blackies Glen.

2.3.2 Fugla Field overlooking Gossa Water in the south of the site is drained to the south by the Burn of Rimminamartha and to the east by the Burn of Amframires (which also drains Flongna Field to the north and Tonga Field to the east). The Burn of Rimminamartha is the primary watercourse entering Gossa Water, which is the only public water supply on Yell. Gossa Water drains east via the Burn of Gossawater into Basta Voe, passing the Scottish Water treatment works at Dalsetter. The intake for the treatment works is located within Gossa Water rather than abstracting from the burn.

2.3.3 Several minor watercourses converge on Gloup Voe in the centre north of the site – the Burn of Rulesgill in the west, the Burns of Hildigill and Thistledale in the east and the Burn of Firth in the south. Tittynans Hill in the southeast of the site is drained to the north by the Burn of Kedillsmires and to the south by the Burn of Dalsetter.

2.3.4 There are numerous artificial drains (or grips) across the site although their locations and density appear to be the result of ad-hoc local attempts to improve drainage rather than systematic attempts to lower water tables.

2.3.5 Average annual rainfall is c.1150mm / year (1931-2014, Shetland Islands Council, 2014), concentrated in the winter months. While this is lower than for many deep peat areas in the UK, the pronounced maritime climate on Yell is also likely to have contributed to deep-peat forming conditions.

2.4. Land Use

2.4.1 Active land use is limited to rough grazing for sheep, with localised cutting just outside the northern site boundary on Sandwater Hill and adjacent to the existing track on the southwest side of Tittynans Hill. Sheep pens, fencing and gates are present in various locations across the site. There is little evidence of burning. The primary function of the area is associated with water supply in the Gossa Water catchment. Infrastructure connecting Gossa Water to a water treatments works in the south of the site near the A968 is visible as a series of monuments and metalled covers running alongside the Burn of Gossawater.

2.4.2 Despite the low intensity of land use, the site has undergone artificial drainage in the form of grips (or moor drains). These are relatively widespread across the site, typically on the midslopes feeding local watercourses (Figure 5).

2.5. Geomorphology

Peat Geomorphology

2.5.1 Digital aerial photography with a ground resolution of 0.25m was used to interpret and map peatland geomorphological features within an earlier iteration of the site boundary. Additional imagery from different epochs available on both Google Earth™ and bing.com/maps was also referred to in order to validate the air photo interpretation. This interpretation and the resulting geomorphological map were subsequently verified during a site walkover undertaken in November 2018 by a Chartered Geologist and experienced peatland geomorphologist with over 20 years' experience of assessing peat landslides. Photos 1 to 11 show typical features identified during the walkovers.

2.5.2 Figure 6 shows the key features and peatland geomorphology of the site. The presence, characteristics and distribution of these features are helpful in understanding the hydrological function of a peatland, the balance of erosion and peat accumulation (or condition), and the sensitivity of a peatland to potential land-use changes.

2.5.3 The highest elevations are characterised by summit mires with extensive pool complexes. Pools range in size from small features >1.0m across to extensive water bodies (up to 90m long and 50m wide; e.g. Photo 1). The majority of pools larger than 10m^2 in area have been mapped and are shown on Figure 6. Most of the pools observed on site were shallow, with bare peat visible under the water surface (Photo 2), often showing evidence of desiccation cracking from drier periods. There was some indication of slow downslope creep of pools, with bulging on the downslope sides (Photo 3) and in some areas, sequences of interconnected former pools that had been drained following collapse of the sidewall of the lowest pool (Photo 4).

2.5.4 The summit pool complexes are drained by a combination of dendritic, linear and anastomosing drainage channels. These channels are frequently small in scale and well vegetated or only visible at the surface as sinuous corridors of sphagnum (Photos 5 and 6). Peat pipes are audible and visible across the site as collapsed pipe ceilings (Photo 7). Some of these subsurface drainage pathways appear to be significant in scale and connected over relatively long distances downslope. Occasionally, surface watercourses are seen crossing over subsurface drainage pathways showing two different 'layers' of water flow within the blanket peat. Where hillsides do not show evidence of natural drainage features, the peat surface is planar and often very wet. Areas without peat or where organic soils are thin typically comprise grassland. Flush zones were observed in some areas and were both wet and soft, however, no areas of quaking bog were identified.

2.5.5 In general, peat erosion is fairly limited and there is very little hagged peat on site. The most pronounced erosion is limited to the margins of the blanket peat along watercourses. Particularly severe erosion is visible along the unnamed watercourse draining Kedills Mires (Photos 8 and 9) with at least 2m thickness of peat undergoing active fluvial incision and undermining.

2.5.6 There is no evidence of large scale peat instability visible on aerial imagery and no peat landslides were observed during site walkovers for both this study and during hydrology and peat depth probing surveys during which all parts of the site were traversed or were visible from opposing slopes. However, there is evidence of localised minor instability in some parts of the site

2.5.7 The majority of 'instability' features appear to relate to small-scale downslope creep of peat deposits on moderate slopes. In these areas, small crescentic headscarps (Photo 10) and tension cracks are visible (typically a few metres in dimension, Photo 11), but there is generally little evidence of downslope deposits such as blocks, rafts or slurry. These forms of instability are focused in the following areas:

- North-east flank of Hill of Vigon above the North Burn of Vigon (tension cracks, tearing and pool collapses, also a number of collapsed pipes, e.g. Photo 7)
- West flank of Muckle Bratt-houll above unnamed tributary to Gloup Voe (minor cracking and localised evidence of pipes)

2.5.8 Areas of bare ground (with exposed mineral substrate) were observed in some gully floors and on some summits, usually in areas of pools and are interpreted to be the dried out footprints of former pool systems (Photo 4).

Peat depth and character

2.5.9 Four phases of peat probing were undertaken in support of site characterisation for the Proposed Development between May 2018 and February 2019. The final probing spread comprises a site-wide 100m grid (one probe per hectare) and detailed infrastructure-specific probing in accordance with SEPA guidelines. In total, 13,061 probes were collected and 174 cores. Further detail is provided in Appendix 10.3 ('Peat Management Plan'). In addition to peat depth, substrate type was assessed using the 'refusal' method which uses a combination of rate of refusal and 'feel' to determine whether soft, granular or bedrock substrates are present below the peat or topsoil.

2.5.10 Interpolation of peat depths was undertaken in the ArcMap GIS environment using a natural neighbour approach. This approach was selected because it preserves recorded depths at each probe location, unlike some other approaches (e.g. kriging), is computationally simple, and minimises 'bullseye' effects. The approach was selected after comparison of outputs with three other methods (inverse distance weight, kriging and TIN).

2.5.11 The peat depth model is shown on Figure 7 with probing locations superimposed. Detailed probing is shown for the full extent of the final layout as well as for some earlier iterations. The model indicates that:

- Peat is generally deep across the full site extent, exceeding 1.0m in depth over a majority of the application area and reaching in excess of 4.0m locally.
- Localised areas of thin peat or organic soil are visible on valley sides or on steeper hillsides (e.g. in the northwest of the site).
- Comparison of the proposed layout with peat depth data indicates that the majority of the deepest peat areas have been avoided by tracks and infrastructure.

2.5.12 Significant efforts were made during layout design to site infrastructure out of the deepest peat areas (within the limits imposed by turbine spacing) and to route access tracks onto shallower peat. Slope angle and the results of preliminary stability analysis were also used as input factors to routing. However, the presence of extensive pool systems on summits and the need to avoid steep slopes while also staying away from watercourses place significant constraints on routing.

2.5.13 Coring of peat across the site (122 locations) and observations in exposed gullies and adjacent to watercourses across the site indicate the peat to comprise a relatively thin and fibrous acrotelm with a significant thickness of well humified (von Post H7-8) catotelmic peat down to substrate (e.g. Photo 8).

2.5.14 The substrate beneath the peat varies in character but is typically rock, gritty sand or sandy silt. No clay till was identified beneath the peat and no iron pans were observed.

3. BACKGROUND TO PEAT INSTABILITY

3.1. Peat Instability in the UK and Ireland

3.1.1 This section reviews published literature to highlight commonly identified landscape features associated with recorded peat landslides in the UK and Ireland. This review forms the basis for identifying similar features at the Proposed Development site and using them to understand the susceptibility of the site to naturally occurring and human induced peat landslides.

3.1.2 Peat instability, or peat landslides, are a widely documented but relatively rare mechanism of peatland degradation that may result in damage to peatland habitats, potential losses in biodiversity and depletion of peatland carbon stores. Three significant peat landslide events occurred in 2003, raising public awareness of peatland hazards (Evans and Warburton, 2007), two of which had natural causes and one occurring in association with a wind farm.

3.1.3 On 19th September 2003, multiple peat landslide events occurred in Pollatomish (Co. Mayo, Ireland; Creighton and Verbruggen, 2003) and in Channerwick in the Southern Shetland Islands (Mills et al, 2007). Both events occurred in response to intense rainfall, possibly as part of the same large scale weather system moving northeast from Ireland across Scotland. The former event damaged several houses, a main road and washed away part of a graveyard. Some of the landslides were sourced from areas of turbary (peat cutting) with slabs of peat detaching along the cuttings. The landslides in Channerwick blocked the main road to the airport and narrowly missed traffic using the road. Watercourses were inundated with peat, killing fish inland and shellfish offshore (Henderson, 2005).

3.1.4 In October 2003, a peat failure occurred on an afforested wind farm site in Derrybrien, County Galway, Ireland, causing disruption to the site and large-scale fish kill in the adjoining watercourses (Lindsay and Bragg, 2004).

3.1.5 The Derrybrien event triggered interest in the influence of wind farm construction and operation on peatlands, particularly in relation to potential risks arising from construction induced peat instability. In 2007, the (then) Scottish Executive published guidelines on peat landslide hazard and risk assessment in support of planning applications for wind farms on peatland sites. While the production of PLHRA reports is required for all Section 36 energy projects on peat, they are now also regarded as best practice for smaller wind farm applications. The guidance was updated in 2017 (Scottish Government, 2017).

3.1.6 Since then, a number of peat landslide events have occurred both naturally and in association with wind farms. In the case of wind farm sites, these have rarely been reported, however landslide scars of varying age are visible in association with wind farm infrastructure on Corry Mountain, Co. Leitrim, at Sonnagh Old Wind Farm, Co. Galway (near Derrybrien; Cullen, 2011), and at Corkey Wind Farm, Co. Antrim. In December 2016, a plant operator was killed during excavation works in peat at the Derrysallagh wind farm site in Co. Leitrim (Flaherty, 2016) on a plateau in which several published examples of instability had been previously reported. A peat landslide was also reported in 2015 near the site of a proposed road for the Viking wind farm on Shetland (The Shetland Times, 2015) though this was not in association with construction works.

3.1.7 Other recent natural events include another failure in Galway at Clifden in 2016 (Irish News, 2016), Cushendall, Co. Antrim (BBC, 2014) and in the Glenelly Valley, Co. Tyrone in 2017 (BBC, 2018). Noticeably, the vast majority of reported failures since 2003 have occurred in Ireland and Northern Ireland, with the one reported Scottish example occurring on the Shetland Islands, an area previously associated with peat instability.

3.1.8 This section of the report provides an overview of peat instability as a precursor to the hazard and risk assessment provided in Sections 4 and 5. Section 3.2 outlines the different types of peat instability documented in the UK and Ireland and. Section 3.3 provides an overview of factors known to contribute to peat instability based on published literature.

3.2. Types of peat instability

3.2.1 Peat instability is manifested in a number of ways (Dykes and Warburton, 2007) all of which can potentially be observed on site either through site walkover or remotely from high resolution aerial photography:

- minor instability: localised and small-scale features that are not generally precursors to major slope failure and including gully sidewall collapses, pipe ceiling collapses, minor slumping along diffuse drainage pathways (e.g. along flushes); indicators of incipient instability including development of tension cracks, tears in the acrotelm (upper vegetation mat), compression ridges, or bulges / thrusts (Scottish Government, 2017); these latter features may be warning signs of larger scale major instability (such as landsliding) or may simply represent a longer term response of the hillslope to drainage and gravity, i.e. creep.

- major instability: comprising various forms of peat landslide, ranging from small scale collapse and outflow of peat filled drainage lines/gullies (occupying a few-10s cubic metres), to medium scale peaty-debris slides in organic soils (10s to 100s cubic metres) to large scale peat slides and bog bursts (1,000s to 100,000s cubic metres).

3.2.2 Evans and Warburton (2007) present useful contextual data in a series of charts for two types of large-scale peat instability – peat slides and bog bursts. The data is based on a peat landslide database compiled by Mills (2002) which collates site information for reported peat failures in the UK and Ireland. Separately, Dykes and Warburton (2007) provide a more detailed classification scheme for landslides in peat based on the type of peat deposit (raised bog, blanket bog, or fen bog), location of the failure shear surface or zone (within the peat, at the peat-substrate interface, or below), indicative failure volumes, estimated velocity and residual morphology (or features) left after occurrence.

3.2.3 For the purposes of this assessment, landslide classification is simplified and split into three main types, typical examples of which are shown in Plate 1. Dimensions, slope angles and peat depths are drawn from charts presented in Evans and Warburton (2007). The term “peat slide” is used to refer to large-scale (typically less than 10,000 of cubic metres) landslides in which failure initiates as large rafts of material which subsequently break down into smaller blocks and slurry. Peat slides occur ‘top-down’ from the point of initiation on a slope in thinner peats (between 0.5 and 1.5m) and on moderate slope angles (typically 5-15°).

3.2.4 The term “bog burst” is used to refer to very large-scale (usually greater than 10,000 of cubic metres) spreading failures in which the landslide retrogresses (cuts) upslope from the point of failure while flowing downslope. Peat is typically deeper (greater than 1.0m and up to 10m) and more amorphous than sites experiencing peat slides, with shallower slope angles (typically 2-5°). Much of the peat displaced during the event may remain within the initial failure zone. Bog bursts are rarely (if ever) reported in Scotland other than in the Western Isles (e.g. Bowes, 1960).

Plate 1 Characteristics landslide types in UK uplands: i) multiple peat slides with displaced slabs and exposed substrate, ii) retrogressive bog burst with peat retained within the failed area, iii) multiple peaty soil slides in a headwater area with displacement of thin soils exposing substrate (all images are at a similar scale and approximately 400m in width)

3.2.5 The term “peaty soil slide” is used to refer to small-scale (1,000s of cubic metres) slab-like slides in organic soils (i.e. they are <0.5m thick). These are similar to peat slides in form, but far smaller and occur commonly in UK uplands across a range of slope angles (Dykes and Warburton, 2007). Their small size means that they often do not affect watercourses and their effect on habitats is minimal.

3.2.6 Few if any spreading failures in peat (i.e. bog bursts) have been reported in Scotland, with only one or two unpublished examples in evidence on the Isle of Lewis. Reports of peat slides are also rare in Scotland in comparison to Ireland, Northern Ireland and England, either because they rarely occur or have not been reported. The deep peat conditions and extensive pool complexes on site are conducive to both peat slides and bog bursts and hence both failure mechanisms are considered in the following analysis.

3.3. Factors contributing to peat instability

3.3.1 Peat landslides are caused by a combination of factors – triggering factors and reconditioning factors (Dykes and Warburton, 2007; Scottish Government, 2017). Triggering factors have an immediate or rapid effect on the stability of a peat accumulation whereas preconditioning factors can influence peat stability over a much longer period. Only some of these factors can be addressed by site characterisation.

3.3.2 Preconditioning factors may influence peat stability over long periods of time (years to hundreds of years), and include:

i) Impeded drainage caused by a peat layer overlying an impervious clay or mineral base (hydrological discontinuity).
ii) A convex slope or a slope with a break of slope at its head (concentration of subsurface flow).
iii) Proximity to local drainage, either from flushes, pipes or streams (supply of water).
iv) Connectivity between surface drainage and the peat/impervious interface (mechanism for generation of excess pore pressures).
v) Artificially cut transverse drainage ditches, or grips (elevating pore water pressures in the basal peat-mineral matrix between cuts, and causing fragmentation of the peat mass).
vi) Increase in mass of the peat slope through peat formation, increases in water content or afforestation.
vii) Reduction in shear strength of peat or substrate from changes in physical structure caused by progressive creep and vertical fracturing (tension cracking or desiccation cracking), chemical or physical weathering or clay dispersal in the substrate.
viii) Loss of surface vegetation and associated tensile strength (e.g. by burning or pollution induced vegetation change).

ix) Increase in buoyancy of the peat slope through formation of sub-surface pools or water-filled pipe networks or wetting up of desiccated areas; and
x) Afforestation of peat areas, reducing water held in the peat body, and increasing potential for formation of desiccation cracks which are exploited by rainfall on forest harvesting.

3.3.3 Triggering factors are typically of short duration (minutes to hours) and any individual trigger event can be considered as the ‘straw that broke the camel’s back’:

i) Intense rainfall or snowmelt causing high pore pressures along pre-existing or potential rupture surfaces (e.g. between the peat and substrate).
ii) Rapid ground accelerations (e.g. from earthquakes or blasting).
iii) Unloading of the peat mass by fluvial incision or by artificial excavations (e.g. cutting).
iv) Focusing of drainage in a susceptible part of a slope by alterations to natural drainage patterns (e.g. by pipe blocking or drainage diversion).
v) Loading by plant, spoil or infrastructure.

3.3.4 External environmental triggers such as rainfall and snowmelt cannot be mitigated against, though they can be managed (e.g. by limiting construction activities during periods of intense rain). Unloading of the peat mass by excavation, loading by plant and focusing of drainage can be managed by careful design, site specific stability analyses, informed working practices and monitoring.

3.4. Consequences of peat instability

3.4.1 Both peat slides and bog bursts have the potential to be large in scale, disrupting large areas of blanket bog and with the potential to discharge large volumes of material into watercourses.

3.4.2 A key part of the risk assessment process is to identify the potential scale of peat instability should it occur and identify the receptors of the consequences. Potential sensitive receptors of peat failure are:

- The development infrastructure and turbines (damage to turbines, tracks, substation, etc).
- Site workers and plant (risk of injury / death or damage to plant).
- Wildlife (disruption of habitat) and aquatic fauna.
- Watercourses and lochs (particularly is associated with public water supply).
- Site drainage (blocked drains / ditches leading to localised flooding / erosion); and
- Visual amenity (scarring of landscape).

3.4.3 While peat failures may cause visual scarring of the peat landscape, most peat failures revegetate fully within 50 to 100 years and are often difficult to identify on the ground after this period of time (Feldmeyer-Christe and Küchler, 2002; Mills, 2002). Typically, it is short-term (seasonal) effects on watercourses that are the primary concern or impacts on public water supply. Gossa Water, which lies within the southern part of the Proposed Development, is a key receptor, particularly given that it provides the only water supply on Yell and is therefore critical infrastructure.

3.5. Good Practice

Scottish Government Guidance

3.5.1 The first edition of the Scottish Government Best Practice Guidance (BPG) was issued in 2007 and provided an outline of expectations for approaches to be taken in assessing peat landslide risks on wind farm sites. After ten years of practice and industry experience, the BPG was reissued in 2017, though without fundamental changes to the core expectations. A key change was to provide clearer steer on the format and outcome of reviews undertaken by the Energy Consents Unit (ECU) checking authority and related expectations of report revisions, should they be required.

3.5.2 In section 4.1 of the BPG, the key elements of a PLHRA are highlighted, as follows (Scottish Government, 2017):

i) An assessment of the character of the peatland within the application boundary including thickness and extent of peat, and a demonstrable understanding of site hydrology and geomorphology.
ii) An assessment of evidence for past landslide activity and present-day instability e.g. pre-failure indicators.
iii) A qualitative or quantitative assessment of the potential for or likelihood of future peat landslide activity (or a landslide susceptibility or hazard assessment).
iv) Identification of receptors (e.g. habitats, watercourses, infrastructure, human life) exposed to peat landslide hazards; and
v) A site-wide qualitative or quantitative risk assessment that considers the potential consequences of peat landslides for the identified receptors.

Section 2 of this report responded to elements i) and ii) and sections 4 and 5 address elements iii)-v).

Approaches to assessing peat instability

3.5.3 This report approaches elements iii) – v) through both a qualitative contributory factor-based approach and via more conventional stability analysis (through limit equilibrium or Factor of Safety (FoS) analysis). The advantage of the former is that many observed relationships between reported peat landslides and ground conditions can be considered together where a FoS is limited to consideration of a limited number of geotechnical parameters. The disadvantage is that the outputs of such an approach are better at illustrating relative variability in landslide susceptibility across a site rather than absolute likelihood.

3.5.4 The advantage of the FoS approach is that clear thresholds between stability and instability can be defined and modelled numerically, however, in reality, there is considerable uncertainty in input parameters and it is a generally held view that the geomechanical basis for stability analysis in peat is limited given the nature of peat as an organic, rather than mineral soil.

3.5.5 To reflect these limitations, both approaches are adopted and outputs from each approach integrated in the assessment of landslide likelihood. In line with the reasoning in paragraph 3.2.6, only peat slides are considered in this assessment. Figure 8 shows the approach.

Approach for the Proposed Development

3.5.6 At the Proposed Development, limit equilibrium methods were used to provide an early screening layer in the project GIS. This screening layer was used to inform the design of the Proposed Development layout including positioning key infrastructure and route track alignments to avoid the areas with the lowest relative stability.

3.5.7 Subsequently, the qualitative approach based on contributory factors was used to provide a second level of analysis. The overall approach to risk is shown schematically in Figure 8 below. The next section provides details of the likelihood assessment.

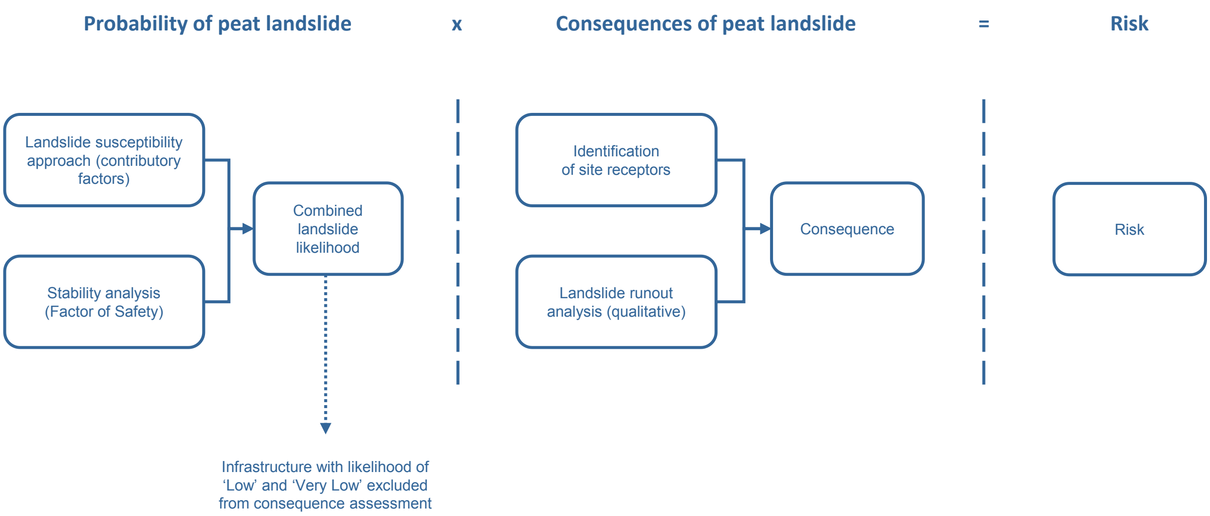


Figure 8 Schematic representation of risk assessment approach

4. ASSESSMENT OF PEAT LANDSLIDE LIKELIHOOD

4.1. Introduction

4.1.1 This section provides details on the landslide susceptibility and limit equilibrium approaches to assessment of peat landslide likelihood used in this report. The assessment of likelihood is a key step in the calculation of risk, where risk is expressed as follows:

Risk = Probability of a Peat Landslide x Adverse Consequences

The probability of a peat landslide is expressed in this report as peat landslide likelihood, and is considered below.

4.2. Limit equilibrium approach

4.2.1 Stability analysis has been undertaken using the infinite slope model to determine the factor of safety for a series of 25m x 25m cells within the Proposed Development boundary. This is the most frequently cited approach to quantitatively assessing the stability of peat slopes (e.g. Scottish Government, 2017; Boylan et al, 2008; Evans and Warburton, 2007; Dykes and Warburton, 2007; Creighton, 2006; Warburton et al, 2003; Carling, 1986). The approach assumes that failure occurs by shallow translational landsliding, which is the mechanism usually interpreted for peat slides. Due to the relative length of the slope and depth to the failure surface, end effects are considered negligible and the safety of the slope against sliding may be determined from analysis of a 'slice' of the material within the slope.

4.2.2 The stability of a peat slope is assessed by calculating a Factor of Safety, F, which is the ratio of the sum of resisting forces (shear strength) and the sum of driving forces (shear stress) (Scottish Government, 2017):

$$F = \frac{c' + (\gamma - h\gamma_w) z \cos^2 \beta \tan \phi'}{\gamma z \sin \beta \cos \beta}$$

4.2.3 In this formula c' is the effective cohesion (kPa), γ is the bulk unit weight of saturated peat (kN/m^3), γ_w is the unit weight of water (kN/m^3), z is the vertical peat depth (m), h is the height of the water table as a proportion of the peat depth, β is the angle of the substrate interface (°) and ϕ' is the angle of internal friction of the peat (°). This form of the infinite slope equation uses effective stress parameters, and assumes that there are no excess pore pressures, i.e. that the soil is in its natural, unloaded condition. The use of cut and fill foundations and tracks across almost the whole construction footprint suggest this is an appropriate approach. The choice of water table height reflects the full saturation of the soils that would be expected under the most likely trigger conditions, i.e. heavy rain.

4.2.4 Where the driving forces exceed the shear strength (i.e. where the bottom half of the equation is larger than the top), F is < 1, indicating instability. A factor of safety between 1 and 1.4 is normally taken in engineering to indicate marginal stability (providing an allowance for variability in the strength of the soil, depth to failure, etc). Slopes with a factor of safety greater than 1.4 are generally considered to be stable.

4.2.5 Where peat is loaded, for example by movement of plant over the bog surface, a total stress approach utilising undrained shear strength can be used. This approach reflects the effects of rapid loading in generating excess pore pressures in the peat (which are unable to drain, reducing frictional resistance between particles).

4.2.6 In this case, the equation is:

$$F = \frac{S_u}{(\gamma z + \gamma_{ct})\sin\beta\cos\beta}$$

S_u is the undrained shear strength and γ_{ct} is the unit weight of construction traffic.

4.2.7 There are numerous uncertainties involved in applying geotechnical approaches to peat, not least because of its high water content, compressibility and organic composition (Hobbs, 1986; Boylan and Long, 2014). Peat comprises organic matter in various states of decomposition with both pore water and water within plant constituents, and the frictional particle-to-particle contacts that are modelled in standard geotechnical approaches are different in peats. There is also a tensile strength component to peat which is assumed to be dominant in the acrotelm, declining with increasing decomposition and depth. As a result, analysis utilising geotechnical approaches is often primarily of value in showing relative stability across a site given credible and representative input parameters rather than in providing an absolute estimate of stability. With this in mind, representative data inputs have been derived from published literature and used in both drained and undrained analyses.

Data Inputs

4.2.8 Stability analysis was undertaken in ArcMap GIS software. A 25m x 25m grid was superimposed on the full site extent and key input parameters derived for each grid cell. In total, c. 35,000 grid cells were analysed. A 25m x 25m cell size was chosen because it is sufficiently small to define a minimum credible landslide size and avoid 'smoothing' of important topographic irregularities. Given the cell size of the input DTM, which provides a key input parameter, any smaller cell size would be unlikely to provide significant benefits.

Parameter	Values	Rationale	Source
Effective cohesion (c')	2, 5	Credible conservative cohesion values for humified peat based on literature review	5.5 - 6.1, peat type not stated (Long, 2005) 3, 4, peat type not stated (Long, 2005) 5, basal peat (Warburton et al., 2003) 8.74, fibrous peat (Carling, 1986) 4, peat type not stated (Dykes and Kirk, 2001) 7 - 12, H8 peat (Huat et al, 2014)
Bulk unit weight (γ)	10.5	Credible mid-range value for humified catotelmic peat	10.8, catotelm peat (Mills, 2002) 10.1, Irish bog peat (Boylan et al 2008)
Effective angle of internal friction (ϕ')	20, 30	Credible conservative friction angles for humified peat based on literature review (only 20° used in analysis)	40 - 65, fibrous (Huat et al, 2014) 50 - 60, amorphous (Huat et al, 2014) 36.6 - 43.5, peat type not stated (Long, 2005) 31 - 55, Irish bog peat (Hebib, 2001) 34 - 48, fibrous sedge pear (Farrell & Hebib, 1998) 32 - 58, peat type not stated (Long, 2005) 23, basal peat (Warburton et al, 2003) 21, fibrous peat (Carling, 1986)
Slope angle from horizontal (β)	Various	Mean slope angle per 25m x 25m grid cell	5m digital terrain model of site

Peat depth (z)	Various	Mean peat depth per 25m x 25m grid cell	Interpolated peat depth model of site
Height of water table as a proportion of peat depth (h)	1	Assumes peat mass is fully saturated (normal conditions during intense rainfall events or snowmelt, which are the most likely natural hydrological conditions at failure)	

Table 1 Geotechnical parameters for drained infinite slope analysis

4.2.9 Table 1 shows the input parameters and assumptions for the stability analyses undertaken. The shear strength parameters c' and ϕ' are usually derived in the laboratory using undisturbed samples of peat collected in the field and therefore site specific values are often not available ahead of detailed site investigation for a development. Therefore, for this assessment, a literature search has been undertaken to identify a range of credible but conservative values for c' and ϕ' quoted in fibrous and humified peats. FoS analysis was undertaken with conservative ϕ' of 20° and values of 2kPa and 5kPa for c'.

4.2.10 Preliminary stability analysis was also undertaken for floating track, assuming representative loads for multi-axle cranes moving over floating road (which is proposed for much of the site). For this analysis, input data corresponded to two representative cases – a 5° slope with 2.5m deep peat and a 10° slope with 1.25m deep peat. The resulting vehicle loaded analysis was then checked against the non-loaded and drained analysis described above. Assumptions are detailed in Table 2.

Parameter	Values	Rationale	Source
Undrained shear strength (Su)	5	Published values show undrained shear strength is typically very similar to effective cohesion (c')	4 - 30, medium and highly humified (Boylan et al, 2008) 4, more humified (Boylan et al, 2008) 5.2, peat type not stated (Long et al, 2005) 5, Irish bog peat (Farrell and Hebib, 1998) 5.7 - 13.2, 4.5 - 6.6, Irish bog peat (Lindsay and Bragg, 2004)
Bulk unit weight (γ)	10.5	Reduction in volume under floating road is balanced by increased density, so pre-load parameters are used	See Table 1
Slope angle from horizontal (β)	5, 10	Slope angles for which floating tracks are proposed	See Table 1
Peat depth (z)	2.5, 1.25	Reduction in volume (i.e. depth) under floating road is balanced by increased density, so pre-load parameters are used	See Table 1

Crane axle load (t)	12	Maximum haul weight that is not considered an "abnormal load"	Assumed

Table 2 Geotechnical parameters and assumptions for undrained infinite slope analysis

Results

4.2.11 The outputs of the drained analysis (effective stress) are shown for both parameter combinations in Figure 9. The more conservative combination (minimum c' and ϕ', left panel) suggests that a considerable proportion of the site is either unstable (F < 1) or of marginal stability (F < 1.4) which is not consistent with site observations nor with the stability of peat in general – peat landslides are very rare occurrences given the wide distribution of peat soils in England, Scotland and Wales. The less conservative combination (right panel) results in more credible results, with only the steepest valley sideslopes showing marginal stability (F < 1.4). These locations often coincide with tension features such as scarps (e.g. Photo 10) and tension cracks (e.g. Photo 11), which are shown in purple on Figure 9.

4.2.12 The general lack of overlap between the Proposed Development infrastructure and areas of lower factor of safety on the right panel are reflective of the use of preliminary factor of safety outputs early in the layout design stage, though inevitably, the use of sideslopes for tracks (in order to avoid summit pool complexes and minimise visual impact) leads to some degree of overlap with lower factor of safety results (notably on the Hill of Vigon).

4.2.13 Output for the undrained analysis is not shown on Figure 9 as it represents a single "worst case" for the maximum slope angle for which floating roads are specified. Relative to the natural case for the same peat depths and slope angles under drained conditions, the calculated factor of safety declines from 2.5 to 1.9 for the 2.5m / 5° case and from 2.4 to 1.5 for the 1.25m / 10° case under undrained (loaded) conditions. This demonstrates that while there is a reduction in stability from loading, it is not a large reduction and falls within acceptable bounds for representative ground conditions on site.

4.3. Landslide susceptibility approach

Overview

4.3.1 The landslide susceptibility approach is based on the layering of contributory factors to produce unique 'slope facets' that define areas of similar susceptibility to failure (Figure 10). The number and size of slope facets will vary from one part of the site to another according to the complexity of ground conditions. In total, c. 9093 facets were considered in the analysis, with an average area of c. 1,800m^3 (or an average footprint of c. 42m x 42m, consistent with smaller to medium scale peaty soil or peat slides reported in the published literature).

4.3.2 Eight contributory factors are considered in the analysis: slope angle (S), peat depth (P), substrate geology (G), peat geomorphology (M), drainage (D), forestry (F), slope convexity (C) and land use (L). For each factor, a series of numerical scores between 0 and 3 are assigned to factor 'classes', the significance of which is tabulated for each factor. The higher a score, the greater the contribution of that factor to instability for any particular slope facet. Scores of 0 imply neutral / negligible influence on instability. Both bog bursts and peat slides were scored, with different classes used for slope angle, peat depth, geomorphology and slope convexity (since the underlying controls for the different landslide types are different).

4.3.3 Factor scores are summed for each slope facet to produce a peat landslide likelihood score (PL_S), the theoretical maximum being 24 (8 factors, each with a maximum score of 3).

$$S_{PL} = S_S + S_P + S_G + S_M + S_D + S_F + S_C + S_L$$

In practice, a maximum score is unlikely, as the chance of all contributory factors having their highest scores in one location is very small.

Slope angle (S)

4.3.4 Table 3 shows the slope ranges, their significance and related scores for the slope angle contributory factor. Slope angles were derived from the 5m digital terrain model and scores assigned based on reported slope angles associated with peat slides rather than a simplistic assumption that 'the steeper a slope, the more likely it is to fail'. Note that the slope model is a TIN (interpolated from irregularly spaced measures of elevation) and these sorts of slope model tend to simplify slopes into triangular surfaces – this can have the effect of steepening or shallowing slopes relative to their actual gradients.

Slope range (°)	Significance	Score (Peat Slide)	Score (Bog Burst)
>20.0	Failure typically occurs as peaty-debris slides due to low thickness of peat	1	0
15.1 - 20.0	Failure typically occurs as peaty-debris slides due to low thickness of peat	2	1
10.1 - 15.0	Failure typically occurs as peat slides, bog slides or peaty-debris slides, a key slope range for reported population of peat failures	3	1
5.1 - 10.0	Failure typically occurs as peat slides, bog slides or peaty-debris slides, a key slope range for reported population of peat failures	3	2
2.1 - 5.0	Failure typically occurs as bog bursts, bog flows or peat flows; peat slides and peaty debris slides rare due to low slope angles	2	3
≤2.0	Failure is very rarely associated with flat ground, neutral influence on stability	0	2

Table 3 Slope classes, significance and scores

4.3.5 Figure 10 shows the distribution of slope angle scores across the site.

Peat depth (P)

4.3.6 Table 4 shows the peat depths, their significance and related scores for the peat depth contributory factor. Peat depths were derived from the peat depth model shown on Figure 7 and reflect the peat depth ranges most frequently associated with peat slides (Evans and Warburton, 2007).

Depth range (m)	Significance	Score (Peat Slide)	Score (Bog Burst)
>1.5	Sufficient thickness for any type of peat failure	2	3
1.0 - 1.5	Sufficient thickness for peat slide or bog slide	3	2
0.5 - 1.0	Sufficient thickness for peat or bog slide and peaty-debris slide but not for bog burst	3	1
<0.5	Organic soil rather than peat, failures would be peaty-debris slides	1	1
No organic soil	No organic soil and therefore failures cannot be interpreted as peat slides, neutral influence on stability	0	0

Table 4 Peat depth classes, significance and scores

4.3.7 Slope facets identified as having 'organic soils', i.e. comprising <0.5m thickness of peat, are still included in the peat landslide susceptibility analysis since landslides with a significant organic soil content are often misinterpreted as peat failures by stakeholders. The distribution of peat depth scores is shown on Figure 10.

Substrate geology (G)

4.3.8 Table 5 shows substrate type, significance and related scores for the peat depth contributory factor. The shear surface or failure zone of peat failures typically overlies an impervious clay or mineral (bedrock) base giving rise to impeded drainage. This, in part, is responsible for the presence of peat, but also precludes free drainage of water from the base of the peat mass, particularly under extreme conditions (such as after heavy rainfall, or snowmelt).

4.3.9 Peat failures are frequently cited in association with glacial till deposits in which an iron pan is observed in the upper few centimetres (Dykes and Warburton, 2007). They have also been observed over glacial till without an obvious iron pan, or over impermeable bedrock. They are rarely cited over permeable bedrock, probably due to the reduced likelihood of peat formation.

Substrate Geology	Significance	Score
Cohesive (clay) glacial till with iron pan	Failures often associated with underlying till, particularly where impermeable iron pan provides polished shear surface	3
Cohesive (clay) glacial till	Failures often associated with underlying till	2
Impermeable bedrock / granular till	Failures sometimes associated with bedrock, particularly if smooth top surface	1
Permeable bedrock	Failures rarely associated with permeable bedrock (peat is often thin or absent), neutral influence on stability	0

Table 5 Substrate geology classes, significance and scores

4.3.10 Probing undertaken across the site indicated primarily bedrock or granular substrates using the refusal method, and coring at 130 locations confirmed this. No iron pans were observed. Accordingly, the full site is treated as if underlain by impermeable bedrock or granular glacial till (Figure 10).

Peat geomorphology (M)

4.3.11 Table 6 shows the geomorphological features identified across the site, their significance and related scores. Being an open moorland site (rather than afforested), there is a strong degree of confidence in the identification and mapping of these features.

Geomorphology	Significance	Score (Peat Slide)	Score (Bog Burst)
Adjacent/upslope (<50m) to existing instability (peat slide, peaty-debris slide, bank failure)	Failures often occur in close proximity to previous failures	3	3
Incipient instability (tension crack, compression ridge, bulging, quaking bog)	Failures are likely to occur where incipient failure morphology is observed	3	3
Intact planar peat	Failures are most frequently recorded in intact peat, planar peat	2	2
Flush / diffuse surface drainage / pool	Failures are often associated with areas of diffuse subsurface drainage (such as flushes)	2	3
Pipe / collapsed pipe	Failures are often associated with areas of soil piping	2	3
Existing peat slide	Failures typically stabilise and do not reactivate after the initial event	1	1
Gullied / dissected / hagged / eroded peat / bare peat / bare ground	Failures are rarely recorded in peat fragmented by erosion	1	1

Table 6 Peat geomorphology classes, significance and scores

4.3.12 Figure 10 shows the geomorphological classes from Figure 6 re-coloured to correspond with Table 6.

Drainage (D)

4.3.13 Table 7 shows artificial and natural drainage feature classes, their significance and related scores. Transverse / oblique drainage lines, both natural and artificial, may reduce peat stability by creating lines of weakness in the peat slope and encouraging the formation of peat pipes. A number of peat failures have been identified which have failed over moorland grips (Warburton et al, 2004). The influence of changes in hydrology becomes more pronounced the more transverse the orientation of the drainage lines relative to the overall slope.

Drainage Feature	Significance	Score
Artificial drain or natural drainage line oblique to slope	Failures are sometimes reported in association with artificial drains oblique/transverse to slope or where undercut by natural drainage lines	3
Artificial drain or natural drainage line aligned to slope	Failures are rarely associated with artificial drains parallel to slope or adjacent to natural drainage lines	1
No artificial or natural drainage lines	Neutral influence on stability	0

Table 7 Drainage feature classes, significance and scores

4.3.14 The effect of drainage lines is captured through the use of a 50m buffer on each natural or artificial drainage line (producing a 100m wide zone of influence) present within peat deposits, noting that many of the headwater streams and larger gullies are in mineral soils in the valley axes (and not in peat). Each buffer is assigned a drainage feature class based on comparison of the drainage axis with elevation contours (oblique or aligned). Individual small-scale gullies are not captured in this approach as they are generally aligned to slope and insufficient in scale. Buffers are shown on Figure 10.

Forestry (F)

4.3.15 Table 8 shows forestry classes, their significance and related scores. A report by Lindsay and Bragg (2004) on Derrybrien suggested that row alignments, desiccation cracking and loading (by trees) could all influence peat stability. This factor is included for completeness (see paragraph 4.3.3), however, there is no afforested terrain within the Proposed Development site. Accordingly, the full site is assigned a score of 0 (Figure 10).

Forestry Class	Significance	Score
Afforested area (with mature trees), ridge and furrows oblique to slope	Peat underlying forestry stands with rows aligned oblique to slope has inter ridge cracks which are conducive to slope instability	2
Afforested area (with mature trees), ridge and furrows aligned to slope	Peat underlying forestry stands with rows aligned with slope is conducive to slope instability, but less so than where rows are aligned oblique to slope	1
Deforested area (few or no trees), ridge and furrows oblique to slope	Peat underlying deforested stands has a higher water table and more neutral buoyancy, but retains inter ridge cracks (lines of weakness) conducive to instability; alignment of cracks oblique to slope is most conducive to instability	3
Deforested area (few or no trees), ridge and furrows aligned to slope	Peat underlying deforested stands has a higher water table and more neutral buoyancy, but retains inter ridge cracks (lines of weakness), however, orientation of these cracks is less critical when aligned to slope	2
Not afforested	Neutral influence on stability	0

Table 8 Forestry classes, significance and scores

Slope convexity (C)

4.3.16 Table 9 shows profile convexity classes, significance and related scores. Convex and concave slopes (i.e. positions in a slope profile where slope gradient changes by a few degrees) have been associated with the initiation point of peat landslides by a number of authors. Convexities are often associated with thinning of peat, such that thicker peat upslope applies stresses to thinner 'retaining' peat downslope. Conversely, buckling and tearing of peat may trigger failure at concavities (e.g. Dykes & Warburton, 2007; Boylan and Long, 2011).

Profile Convexity	Significance	Score
Convex Slope	Peat failures are often reported on or above convex slopes	3
Concave Slope	Peat failures are occasionally reported in association with concave slopes	2
Rectilinear Slope	Rectilinear slopes show no particular predisposition to failure, neutral influence on stability	0

Table 9 Profile convexity classes, significance and scores

4.3.17 The 5m digital terrain model and OS contours were used to identify areas of noticeable slope convexity across the site (Figure 10). Concavities were generally absent or in areas without peat (i.e. at the change from valley sideslopes to valley floors). Axes of convexity (running along the contour) were assigned a 50m buffer to produce 100m (upslope to downslope) convexity zones and these were assigned scores in accordance with Table 9.

Land use (L)

4.3.18 Table 10 shows land use classes, significance and related scores. A variety of land uses have been associated with peat failures (see Section 3.3). While it is hypothesised that burning may cause desiccation cracking in peat and facilitate water flows to basal peat (and potential shear surfaces), there is little evidence directly relating burnt ground to peat landslide events. Cutting is minimal and confined to the southeast of the site. A score of 1 is applied in burnt areas and 3 to cutover areas (shown on Figures 5 and 10).

Land Use	Significance	Score
Cutting / turbary	Failures are often associated with peat cuttings / turbary	3
Adjacent quarrying	Failures are occasionally reported adjacent to quarries (usually as bog bursts, bog flows or peat flows)	2
Burning	Failures are rarely associated with burning though this activity may create pathways for water to the base of peat	1
Other land use	Failures are rarely associated with other forms of land use	0

Table 10 Land use classes, significance and scores

Generation of slope facets

4.3.19 The eight contributory factor layers shown on Figure 10 were combined in ArcMap to produce approximately 21,000 slope facets. Scores for each facet were then summed to produce a peat landslide likelihood score. These likelihood scores were then converted into descriptive 'likelihood classes' from 'Very Low' to 'Very High' with a corresponding numerical range of 1 to 5 (in a similar format to the Scottish Government BPG).

Summed Score from Contributory Factors	Typical site conditions associated with score	Likelihood (qualitative)	Peat landslide likelihood score
≤ 6	Unmodified peat with no more than low weightings for peat depth, slope angle, underlying geology and peat morphology	Very Low	1
7 - 11	Unmodified or modified peat with no more than moderate or some high scores for peat depth, slope angle, underlying geology and peat morphology	Low	2
12 - 16	Unmodified or modified peat with high scores for peat depth and slope angle and / or high scores for at least three other contributory factors	Moderate	3
17 - 21	Modified peat with high scores for peat depth and slope angle and several other contributory factors	High	4
> 21	Modified peat with high scores for most contributory factors (unusual except in areas with evidence of incipient instability)	Very High	5

Table 11 Likelihood classes derived from the landslide susceptibility approach

4.3.20 Table 11 describes the basis for the likelihood classes. A judgement was made that for a facet to have a moderate or higher likelihood of a peat landslide, a likelihood score would be required equivalent to both the worst case peat depth and slope angle scores (3 in each case, i.e. 3 x 2 classes) alongside three intermediate scores (of 2, i.e. 2 x 3 classes) for other contributory factors. This means that any likelihood score of 12 or greater would be equivalent to at least a moderate likelihood of a peat landslide. Given that the maximum score attainable is 24, this seems reasonable.

Results

4.3.21 The left panel of Figure 11 shows the outputs of the landslide susceptibility approach for peat slides. The results indicate that the majority of the site has a 'Low' to 'Very Low' likelihood of a peat slide under natural conditions. Areas of 'Moderate' likelihood are typically located on moderate slopes or in areas of slope convexity. There are no areas identified with 'High' or 'Very High' landslide susceptibility. In common with the stability analysis approach, the outputs of this approach indicate the majority of the site to be stable under natural conditions, which is in accordance with site observations.

4.3.22 The right side of Figure 11 shows the equivalent outputs for bog bursts. The results of the analysis indicate less of the site to be of 'Very Low' susceptibility but only minor increases in Moderate susceptibility. Again, there are no 'High' or 'Very High' susceptibility areas. The slightly higher scores for bog burst than peat slide are likely to reflect the deeper peat present over much of the site (deep peat being more frequently associated with bog burst failures).

Combined landslide likelihood

4.3.23 Figure 12 shows in purple any proposed areas of infrastructure intersecting with areas of moderate or higher landslide susceptibility (from the contributory factor approach) or Factor of Safety of 1.4 or less (from the limit equilibrium approach). All other infrastructure are shown in grey). In order for there to be a "Medium" or "High" risk (Scottish Government, 2017), likelihoods must be "Moderate" or higher (see Figure 13 below) and hence this provides a screening basis for the likelihood results. In all, 22 infrastructure locations overlap with areas of "Moderate" landslide likelihood. No areas are calculated to have "High" or "Very High" likelihoods.

Peat landslide likelihood (scores bracketed)	Adverse Consequence (scores bracketed): Very High (5)	High (4)	Moderate (3)	Low (2)	Very Low (1)
Very High (5)	High	High	Medium	Medium	Low
High (4)	High	Medium	Medium	Low	Negligible
Moderate (3)	Medium	Medium	Low	Low	Negligible
Low (2)	Low	Low	Low	Negligible	Negligible
Very Low (1)	Low	Negligible	Negligible	Negligible	Negligible

Risk Level	Action suggested for each zone
High	Avoid project development at these locations
Medium	Project should not proceed unless risk can be avoided or mitigated at these locations, without significant environmental impact, in order to reduce risk ranking to low or negligible
Low	Project may proceed pending further investigation to refine assessment and mitigate hazard through relocation or re-design at these locations
Negligible	Project should proceed with monitoring and mitigation of peat landslide hazards at these locations as appropriate

Figure 13 Top: Risk ranking as a product of likelihood and consequence; Bottom: suggested action given each level of calculated risk (after Scottish Government, 2017)

4.3.24 Section 5 of this report describes the consequence assessment and risk calculation for all areas where infrastructure intersects "Moderate" likelihood of a peat landslide.

5. ASSESSMENT OF CONSEQUENCE AND RISK

5.1. Introduction

5.1.1 In order to calculate risks, the potential consequences of a peat landslide must be determined. This requires identification of receptors and an assessment of the consequences for these receptors should a peat landslide occur. This section describes the consequence assessment and then provides risk results based on the product of likelihood and consequence (as described in paragraph 4.1.1).

5.2. Receptors

5.2.1 At the Proposed Development site there are four primary receptors: watercourses, non-riverine habitats (e.g. groundwater dependent terrestrial ecosystems or GWDTEs), a public water supply and infrastructure (both related to the water supply and associated with the Proposed Development). These are considered below.

Watercourses

5.2.2 The Proposed Development site is drained by numerous watercourses, many of which drain directly to the west coast or to the sea via Gloup Voe to the north. However, some tributaries drain directly into Gossa Water, which is the only public water supply for Yell and is therefore regarded as critical infrastructure. Any direct or indirect impact on Gossa Water by a landslide occurring within this part of the site would be considered a serious consequence, and accordingly is assigned a maximum consequence score of 5 (Table 12). The Burn of Gossawater, which flows out of Gossa Water, is downstream of the intake and therefore any effects on the burn would not directly affect water supply.

5.2.3 Elsewhere, watercourses are assigned a consequence score of 3 (due to the potential short to medium term impacts on locally important riverine habitats). No private water supplies have been identified as hydrologically connected to the site.

Receptor	Consequence	Score	Justification for Consequence Score
Watercourses	Short term increase in turbidity and acidification, potential fish kill	3	Watercourses are locally important with no connectivity to larger river systems
Infrastructure (Public Water Supply)	Medium term increase in turbidity, acidification and changes to water colour	5	Only public water supply on Yell and therefore maintenance of supply is critical
Open blanket bog habitats	Short to medium term loss of vegetation cover, disruption of peat hydrology, carbon release	3	Blanket bog is a high quality habitat, though the effects of peat landslides on habitats are generally shortlived
Wind farm Infrastructure	Damage to infrastructure, possible injury, loss of life	5	Loss of life, though very unlikely, is a severe consequence; financial implications of damage and re-work are less significant

Table 12 Receptors considered in the consequence analysis

Habitats

5.2.4 While blanket bog habitats are valuable, they generally recover from instability events through revegetation over a matter of decades and therefore a consequence score of 3 is assigned for all habitats within the Proposed Development site (Table 12).

Infrastructure

5.2.5 The Proposed Development site is relatively isolated, with non-wind farm infrastructure limited to the Old Cullivoe Road to the east of the site and to buried infrastructure associated with the public water supply. The approximate alignment of a buried pipeline connecting the Gossa Water intake to the water treatment works outside the site boundary is shown on Figure 5. The pipeline position is indicated on the ground by a series of hatches and concrete monuments. This infrastructure is unlikely to be impacted by a peat landslide, since the most likely landslide source areas (shown on Figure 12) are upslope of the pipeline and runout tends to occur overground (and would likely flow around the monuments. Nevertheless, potential impacts on public water supply are assigned the maximum consequence score of 5.

5.2.6 Infrastructure that would be affected in the event of a peat landslide would be Proposed Development infrastructure. These effects would be most likely during construction, at which time personnel would be using the access track network or be present at infrastructure locations for long periods. While commercial losses would be important to the Applicant, loss of life / injury would be of greater concern, and a consequence score of 5 is assigned for any infrastructure locations subject to potential peat landslides (Table 12).

5.3. Consequences

5.3.1 A consequence assessment has been undertaken by determining the potential for landslides sourced at infrastructure locations with a moderate natural likelihood of peat instability to impact the receptors identified above. For example, if a turbine is located in a moderate (likelihood score of 3) area and is located 50m from a watercourse (with a consequence score of 5), there is a high likelihood that a landslide triggered during construction would reach that watercourse. The calculated risk would be a product of the likelihood and consequence scores (likelihood: 3 x consequence: 5 = risk: 15, see Figure 13) and be equivalent to a “Medium” risk.

5.3.2 Figure 12 shows all infrastructure locations that overlap with moderate likelihoods, based on the combined landslide likelihood scores described in Section 4. In order to determine the likelihood of impact on watercourses and infrastructure, ‘runout pathways’ have been defined that show the estimated maximum footprint of the landslide. At peat slide locations, the footprint is taken to be the first 50m downslope of the infrastructure. Where bog burst likelihoods are moderate or higher, the 50m area upslope of the infrastructure is also included in the footprint (making a larger failure). This is considered to be a conservative approach.

5.3.3 Runout pathways are divided in a downslope direction into 50m, 100m, 250m and 500m zones on the basis of typical runout distances detailed in Mills (2002). The likelihood of runout passing from one runout zone to the next (e.g. from the 50m zone into the 100m zone) is based on the proportion of the published peat landslide population that reaches each runout distance on Figure 13 (0-50m: 100%, 50-100m: 87%, 100-250m: 56%, 250-500m: 44%). The first 50m includes the landslide source area.

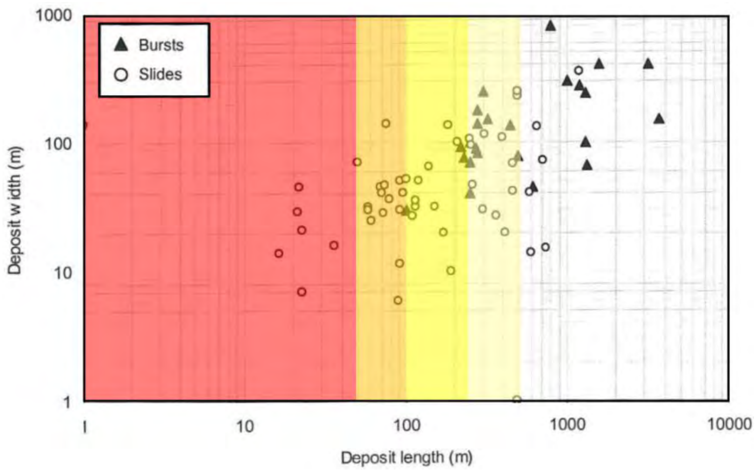


Figure 14 Runout distances for published peat landslides, colours on plot correspond to runout pathways on Figure 12 (after Mills, 2002)

5.3.4 Additional analysis was also performed to determine whether a landslide, once initiated, would become exhausted of material as it thinned downslope. The analysis assumed a source volume equivalent to the source footprint multiplied by the average peat depth in the source area (from the peat depth model). This volume was then distributed over the full runout pathway (i.e. mobilised volume / runout area) to generate an average thickness of deposit. As the runout length increases, the volume thins, in keeping with observed peat landslide deposits.

5.3.5 This analysis indicated that in all cases, sufficient material would be available to reach the end of the 500m zone, though in a handful of cases (source areas 4, 8, 14 and 17), the thickness at the end of the runout pathway would be <20cm and in likelihood these runout deposits would by arrested by the roughness of vegetation rather than continue moving downslope for the full runout pathway length.

5.4. Calculated risk

5.4.1 Risk levels have been calculated as a product of likelihood and consequence and are shown on Figure 15 for each runout envelope. Each runout zone is colour coded to match the risk rankings shown in Figure 13. For each zone, the score for the most sensitive receptor has been chosen for the risk calculation (i.e. a conservative approach). For example, if the 50-100m zone includes both a watercourse feeding Gossa Water (consequence score of 5) and open bog habitat (consequence score of 3), a consequence score of 5 is used in the risk calculation.

5.4.2 Figure 15 indicates that of the 22 infrastructure locations overlapping with “Moderate” landslide likelihoods, ten locations have “Medium” risks (locations 1, 4, 10-14, 16, 18 and 19) within one or more of their runout zones. The source zones (black circles with white text on Figure 15), relevant infrastructure and primary receptor (bracketed) are listed below:

- Source zone 1: Track from Turbine 1 to Turbine 2 (South Burn of Vigon).
- Source zone 4: Track between Turbines 5 and 6 (Proposed Development infrastructure / Burn of Rulesgill).
- Source zone 10: Junction of tracks to Turbines 8 and 9 (Proposed Development infrastructure).
- Source zone 11: Blade fingers and turning head for Turbine 14 (Unnamed tributary to Burn of Gossawater / buried Scottish Water infrastructure).

- Source zone 12: Junction at Turbine 13 (Proposed Development infrastructure).
- Source zone 13: Turbine 15 (Burn of Gossawater / buried Scottish Water infrastructure).
- Source zone 14: Turbine 18 (Riven Burn).
- Source zone 16: Track from Turbines 17 and 18 to Turbine 23 (Burn of Kedillsmires).
- Source zone 18: Track from Turbine 24 to Turbine 25 (Burn of Kedillsmires).
- Source zone 19: Track from Turbine 23 to Turbine 25 and northeast corner of Borrow Pit C (Burn of Kedillsmires)

5.4.3 No source locations have a “High” calculated risk and the other twelve locations have “Low” calculated risks. The tributaries to Gossa Water in the southwest of the site have “Low” calculated risks for their respective source zones (8 and 9) throughout their full runout envelopes. Runout from source zone 11 does not reach the Scottish Water buried pipeline while source zone 13 has a “Low” calculated risk where it overlaps with the pipeline.

5.4.4 The “Medium” risk locations are primarily associated with impacts on the Proposed Development infrastructure and minor watercourses. Section 6 considers how these risks may be reduced post-consent through further assessment and refinement.

6. RISK MITIGATION

6.1. Overview

6.1.1 A number of mitigation opportunities exist to reduce the risk levels identified at the Proposed Development site. These range from infrastructure specific measures (which may act to reduce peat landslide likelihood, and, in turn, risk) to general good practice that should be applied across the site to engender awareness of peat instability and enable early identification of potential displacement and opportunities for mitigation.

6.1.2 Risks may be mitigated by:

i) Undertaking site specific stability analysis using better quality topographic data, final design loads for infrastructure and detailed ground models in areas of specific concern (e.g. the 10 locations discussed in section 5.4).
ii) Post-consent analysis of the effects of drains on areas identified with Moderate likelihoods – at present, where drains are aligned oblique to slope, they are assigned worst case scores in the likelihood assessment and these may be overly conservative.
iii) Precautionary construction measures - use of monitoring, good practice and a geotechnical risk register in all locations.

6.1.3 Based on the analysis presented in this report, mitigation measures have been identified for the 10 "Medium" and 12 "Low" locations, and these are detailed below in section 6.2 and in Table 13. General good practice is outlined in sections 6.3 and 6.4.

6.2. Proposed mitigation

6.2.1 Table 13 lists the 22 locations (labelled by source zone) of “Low” or “Medium” risk, the sections of infrastructure associated with the risk level, the key receptor identified in the consequence assessment, indicative runout thickness at the receptor, location specific mitigation measures and their anticipated effect in risk reduction relative to the calculated risk.

6.2.2 A variety of mitigation measures are recommended, some of which involve reducing conservatism in the risk assessment e.g. by de-risking drains through site specific analysis or by acquisition of better quality slope data (see paragraphs 6.2.5 and 6.2.6 below).

6.2.3 In other cases, on-site measures could be implemented, such as installation of catch-fences as a precaution against runout into sensitive watercourses (e.g. in the southwest of the site).

6.2.4 Finally, preparation of a geotechnical risk register (GRR) providing explicit mitigation measures tailored to each “Medium” or “Low” risk location will enable risks to be further minimised. The GRR will provide a series of measures detailing additional site investigation and assessment needs, indicating site specific features that may require active management during construction (e.g. pool complexes, drains), provide monitoring protocols to identify any early signs of reduced stability during construction works, and control measures to address unanticipated ground displacement.

6.2.5 For most locations, detailed site specific stability analysis has been recommended to determine whether the current level of analysis is overly conservative. The primary source of uncertainty in relation to current inputs is the slope model used in both the qualitative and quantitative likelihood approaches. The TIN model used for the slope map tends to oversimplify the slope geometry, steepening and softening slopes (dependent on the locations and separation of elevation data used in the model, see paragraph 4.3.4).

Source Zone	Infrastructure	Key Receptor	Runout depth at key receptor	Calculated Risk Level	Location Specific Mitigation	Residual Risk
1	Track from Turbine 1 to Turbine 2	South Burn of Vigon	0.9m	Medium	• Site specific stability analysis based on local peat data • Investigate and manage drains in source zone • Ensure no connectivity between working area and upslope summit pool complex • Close monitoring of track construction works	Low
2	Turbine 2 and Borrow Pit I	Unnamed tributary to North Burn of Vigon	0.4m	Low	• Investigate and manage drains in source zone • Ensure no connectivity between working area and upslope summit pool complex • Close monitoring of excavation works	Negligible
3	Turbine 3 and track to Turbine 6	Burn of Riggadale	0.7m	Low	• Ensure no connectivity between working area and upslope summit pool complex • Drain pools overlapping footprint prior to construction • Close monitoring of excavation works and track construction	Low
4	Track between Turbine 5 and Turbine 6	Wind farm infrastructure / Burn of Rulesgill	0.18m	Medium	• Investigate and manage drains in source zone • Close monitoring of track construction	Low
5	Turbine 6	Burn of Rulesgill	0.4m	Low	• Investigate and manage drains in source zone • Close monitoring of excavation works	Negligible
6	Turning head for Turbine 29	Gloup Voe (inlet)	0.2m	Low	• Ensure no connectivity between working area and upslope summit pool complex • Drain pools overlapping footprint prior to construction • Close monitoring of track construction	Negligible
7	Track from Turbine 28 to Turbine 29	Gloup Voe (inlet)	0.2m	Low	• Close monitoring of track construction • Consider excavation rather than floating to remove source material	Low
8	Track from Turbine 10 to Turbine 12	Burn of Rimminamartha	0.2m	Low	• Install catch fence set-back from stream to arrest minimal potential debris thickness (0.20m) • Investigate and manage drains in source zone • Close monitoring of excavation works	Negligible
9	Turbine 12 and associated track	Burn of Rimminamartha	0.4m	Low	• Install double catch fence set-back from stream to arrest potential debris thickness (0.40m) • Drain / divert peat pipe • Investigate and manage drains in source zone • Close monitoring of excavation works	Negligible
10	Junction of tracks to Turbines 8 and 9	Wind farm infrastructure	1.4m	Medium	• Close monitoring of track construction • Consider excavation rather than floating to remove source material	Negligible
11	Blade fingers and turning head for Turbine 14	Unnamed tributary to Burn of Gossawater / buried infrastructure	0.6m	Medium	• Site specific stability analysis based on local peat data • Close monitoring of excavation works	Low
12	Junction at Turbine 13	Wind farm infrastructure	0.3m	Medium	• Site specific stability analysis based on local peat data • Investigate and manage drains in source zone • Close monitoring of track construction	Low
13	Turbine 15	Burn of Gossawater / buried infrastructure	0.6m	Medium	• Investigate and manage drains in source zone • Close monitoring of track construction	Low
14	Turbine 18	Riven Burn	0.15m	Medium	• Install catch fence set-back from stream to arrest minimal potential debris thickness (0.20m) • Site specific stability analysis based on local peat data • Close monitoring of excavation works	Low
15	Track to Turbine 22	Burn of Kedillsmires	0.4m	Low	• Site specific stability analysis to ensure safe excavations • Close monitoring of excavation works	Low
16	Track from Turbines 17 and 18 to Turbine 23	Burn of Kedillsmires	1.3m	Medium	• Close monitoring of track construction • Consider excavation rather than floating to remove source material	Negligible
17	Turbine 24	Burn of Kedillsmires	0.2m	Low	• Investigate and manage drains in source zone • Close monitoring of excavation works	Negligible
18	Track from Turbine 24 to Turbine 25	Burn of Kedillsmires	0.2m	Medium	• Investigate and manage drains in source zone • Close monitoring of track construction	Low
19	Track from Turbine 23 to Turbine 25, Borrow Pit C	Burn of Kedillsmires	0.2m	Medium	• Investigate and manage drains in source zone • Close monitoring of track construction	Low
20	Track to Turbine 25	Burn of Kedillsmires	0.8m	Low	• Investigate and manage drains in source zone • Close monitoring of track construction	Low
21	Turbine 25 and associated track	Burn of Kedillsmires	0.75m	Low	• Investigate and manage drains in source zone • Ensure no connectivity between working area and upslope summit pool complex • Drain pools overlapping footprint prior to construction • Close monitoring of excavation works and track construction	Negligible
22	Turbine 25	Burn of Kedillsmires	0.2m	Low	• Install catch fence set-back from stream to arrest minimal potential debris thickness (0.20m) • Investigate and manage drains in source zone • Ensure no connectivity between working area and upslope summit pool complex • Drain pools overlapping footprint prior to construction • Close monitoring of excavation works and track construction	Negligible

Table 13 Mitigation measures for areas with “Medium” and “Low” risks

This could be addressed by the acquisition of engineering quality elevation data along the proposed track alignments and at infrastructure locations (for example through the use of a UAV to collect up-to-date elevation data and aerial photographs).

6.2.6 A second area where the analysis may be over-conservative is in the estimate of drainage effects on the surrounding peat slopes. As noted in paragraph 4.3.14, 50m buffers were applied to each artificial drainage line, and these areas are often associated with areas of higher landslide likelihood (and, in turn, risk). Post-consent, site-based review of the areas surrounding these drains may aid in reducing the assessed risks at some locations.

6.2.7 The specification of floating track as the primary construction method for the majority of tracks limits slope cutting, which is the primary cause of bog burst failures. Close monitoring of track alignments during and following installation and areas upslope of excavations (i.e. turbines, hardstandings and borrow pits) will be of value in identifying unanticipated ground displacements before they represent a risk to receptors.

6.3. Good practice during construction

6.3.1 Assuming detailed design informed by site specific stability analysis has enabled refinement of suitable locations and foundation conditions for proposed infrastructure, the following good practice should be undertaken during construction:

6.3.2 For excavations:

- Use of appropriate supporting structures around peat excavations (e.g. for turbines, crane pads and compounds) to prevent collapse and the development of tension cracks.
- Avoid cutting trenches or aligning excavations across slopes (which may act as incipient back scars for peat failures) unless appropriate mitigation has been put in place.
- Implement methods of working that minimise the cutting of the toes of slope, e.g. working up-to-downslope during excavation works.
- Monitor the ground upslope of excavation works for creep, heave, displacement, tension cracks, subsidence or changes in surface water content.
- Monitor cut faces for changes in water discharge, particularly at the peat-substrate contact.
- Minimise the effects of construction on natural drainage by ensures natural drainage pathways are maintained or diverted such that there is no significant alteration of the hydrological regime of the site; drainage plans should avoid creating drainage/infiltration areas or settlement ponds towards the tops of slopes (where they may act to both load the slope and elevate pore pressures).

6.3.3 For cut tracks:

- Maintain drainage pathways through tracks to avoid ponding of water upslope.
- Monitor the top line of excavated peat deposits for deformation post-excavation.
- Monitor the effectiveness of cross-track drainage to ensure it water remains free-flowing and that no blockages have occurred.

6.3.4 For floating tracks:

- Allow peat to undergo primary consolidation by adopting rates of road construction appropriate to weather conditions.

- Monitor the effects of secondary compression over the life of the Proposed Development while the tracks are utilised (up to 30 years) to ensure running surfaces remain elevated above the ground surface and do not cause ponding.
- Identify ‘stop’ rules, i.e. weather dependent criteria for cessation of track construction based on local meteorological data.
- Run vehicles at 50% load capacity until the tracks have entered the second compression phase.
- Prior to construction, setting out the centreline of the proposed track to identify any ground instability concerns or particularly wet zones.

6.3.5 For storage of peat and for restoration activities:

- Ensure stored peat is not located in areas identified with ‘Moderate’ or higher peat landslide likelihoods or within areas of “Medium” or higher risk.
- Undertake site specific stability analysis for all areas of peat storage to ensure the likelihood of destabilisation of underlying peat is minimised.
- Ensure retaining berms within borrow pits are sufficiently keyed into the substrate to remain in-situ and ensure they are structural competent to accommodate lateral pressures from retained peat deposits.
- Avoid storing peat on slope gradients >3° and preferably store on ground with neutral slopes and natural downslope barriers to peat movement.
- Monitor effects of wetting / re-wetting stored peat on surrounding peat areas, and prevent water build up on the upslope side of peat mounds.
- Undertake regular monitoring of emplaced peat in restoration areas to identify evidence of creep or pressure on retaining structures (dams and berms).
- Maximise the interval between material deliveries over newly constructed tracks that are still observed to be within the primary consolidation phase.

6.3.6 In addition to these control measures, the following good practice should be followed:

- A geotechnical risk register should be prepared for the site following intrusive investigations post-consent and location specific stability analyses – the risk register should be considered a live document and updated with site experience as infrastructure is constructed.
- Full site walkovers should be undertaken at scheduled intervals to be agreed with the Local Authority to identify any unusual or unexpected changes to ground conditions (which may be associated with construction or which may occur independently of construction).
- All construction activities and operational decisions that involve disturbance to peat deposits should be overseen by an appropriately qualified geotechnical engineer with experience of construction on peat sites.
- Awareness of peat instability and pre-failure indicators should be incorporated in site induction and training to enable all site personnel to recognise ground disturbances and features indicative of incipient instability.
- Monitoring checklists should be prepared with respect to peat instability addressing all construction activities proposed for site.

6.4. Good practice post-construction

6.4.1 Following cessation of construction activities, monitoring of key infrastructure locations should continue by full site walkover to look for signs of unexpected ground disturbance, including:

- Ponding on the upslope side of infrastructure sites and on the upslope side of access tracks.
- Subsidence and lateral displacement of tracks.
- Changes in the character of natural peat drainage within a 50m buffer strip of tracks and infrastructure (e.g. gullies changing to bog pools, development of quaking bog).
- Blockage or underperformance of the installed site drainage system.
- Slippage or creep of stored peat deposits (including in restored peat cuttings).
- Development of tension cracks, compression features, bulging or quaking bog anywhere in a 50m corridor surrounding the site of any construction activities or site works.

6.4.2 This monitoring should be undertaken on a quarterly basis in the first year after construction, biannually in the second year after construction and annually thereafter; in the event that unanticipated ground conditions arise during construction, the frequency of these intervals should be reviewed, revised and justified accordingly.

7. REFERENCES

BBC (2014) Torrential rain leads to landslides in County Antrim. https://www.bbc.co.uk/news/uk-northern-ireland-28637481 accessed 19/07/2018
BBC (2018) Glenelly Valley landslides were 'one-in-3,000 year event'. https://www.bbc.co.uk/news/uk-northern-ireland-43166964 accessed 19/07/2018
Boylan N, Jennings P and Long M (2008) Peat slope failure in Ireland. Quarterly Journal of Engineering Geology, 41, pp. 93–108
Boylan N and Long M (2011) In situ strength characterisation of peat and organic soil using full-flow penetrometers. Canadian Geotechnical Journal, 48(7), pp1085-1099
Boylan N and Long M (2014) Evaluation of peat strength for stability assessments. Geotechnical Engineering, 167, pp422-430
Bowes DR (1960) A bog-burst in the Isle of Lewis. Scottish Geographical Journal. 76, pp. 21-23
Carling PA (1986) Peat slides in Teesdale and Weardale, Northern Pennines, July 1983: description and failure mechanisms. Earth Surface Processes and Landforms, 11, pp. 193-206
Creighton R (Ed) (2006) Landslides in Ireland. Geological Society of Ireland, Irish Landslides Working Group, 125p
Creighton R and Verbruggen K (2003) Geological Report on the Pollatomish Landslide Area, Co. Mayo. Geological Survey of Ireland, 13p
Cullen C (2011) Peat stability – minimising risks by design. Presentation at SEAI Wind Energy Conference 2011, 45p
Dykes AP and Kirk KJ (2001) Initiation of a multiple peat slide on Cuilcagh Mountain, Northern Ireland. Earth Surface Processes and Landforms, 26, 395-408
Dykes A and Warburton J (2007) Mass movements in peat: A formal classification scheme. Geomorphology 86, pp. 73–93
Evans MG & Warburton J (2007) Geomorphology of Upland Peat: Erosion, Form and Landscape Change, Blackwell Publishing, 262p
Farrell ER and Hebib S (1998) The determination of the geotechnical parameters of organic soils, Proceedings of International Symposium on Problematic Soils, IS-TOHOKU 98, Sendai, 1998, Japan, pp. 33–36
Feldmeyer-Christe E and Küchler M (2002) Onze ans de dynamique de la vegetation dans une tourbiere soumise a un glissement de terrain. Botanica Helvetica 112, 103-120
Hebib S (2001) Experimental investigation of the stabilisation of Irish peat, unpublished PhD thesis, Trinity College Dublin
Henderson S (2005) Effects of a landslide on the shellfish catches and water quality in Shetland. Fisheries Development Note No. 19, North Atlantic Fisheries College
Hobbs NB (1986) Mire morphology and the properties and behaviour of some British and foreign peats. Quarterly Journal of Engineering Geology, London, 1986, 19, pp. 7–80
Flaherty R (2016) Man dies in suspected landslide at wind farm in Co Sligo. Irish Times, 13/12/2013, https://www.irishtimes.com/news/crime-and-law/man-dies-in-suspected-landslide-at-wind-farm-in-co-sligo-1.2903750, accessed 19/07/2018
Huat BBK, Prasad A, Asadi A and Kazemian S (2014) Geotechnics of organic soils and peat. Balkema, 269p
Irish News (2016) Major landslide sees 4,000 tonnes of bog close popular Galway tourist route. https://www.independent.ie/irish-news/major-landslide-sees-4000-tonnes-of-bog-close-popular-galway-tourist-route-34830435.html accessed 19/07/2018
Lindsay RA and Bragg OM (2004) Wind farms and blanket peat. A report on the Derrybrien bog slide. Derrybrien Development Cooperative Ltd, Galway, 149p
Long M (2005) Review of peat strength, peat characterisation and constitutive modelling of peat with reference to landslides. Studia Geotechnica et Mechanica, XXVII, 3-4, pp. 67–88
Mills AJ, Moore R, Carey JM and Trinder SK (2007) Recent landslide impacts in Scotland: possible evidence of climate change? In. McInnes, R. et al (Eds) Landslides and climate change: challenges and solutions, Proceedings of Conference, Isle of Wight, 2007
Mills AJ (2002) Peat slides: Morphology, Mechanisms and Recovery, unpublished PhD thesis, University of Durham
Scottish Government (2017) Peat Landslide Hazard and Risk Assessments, Best Practice Guide for Proposed Electricity Generation Developments (Second Edition). Scottish Government, 84p
Shetland Islands Council (2014) Shetland in Statistics. Shetland Islands Council Economic Development Service, 61p

The Shetland Times (2015) Mid Kame landslip on proposed windfarm site. http://www.shetlandtimes.co.uk/2015/10/30/mid-kame-landslip-on-proposed-windfarm-site accessed 19/07/2018

Warburton J, Holden J and Mills AJ (2004). Hydrological controls of surficial mass movements in peat. Earth Science Reviews, 67, pp. 139-156

Warburton J, Higgitt D and Mills AJ (2003) Anatomy of a Pennine peat slide, Northern England. Earth Surface Processes and Landforms, 28, pp. 457-473

PHOTOS

Photo 1 Summit pool complex on Tonga Field, pools are generally shallow with visible bottoms

Photo 2 Desiccation cracking at the base of a pool (caused by irreversible drying during dry periods)

Photo 3 Failing front face of bog pool

Photo 4 Upper (former) pool drained into lower pool

Photo 5 Sinuous diffuse surface drainage pathway (largely sphagnum below below water surface)

Photo 6 Sphagnum and Juncus (reeds) in diffuse surface drainage pathway

Photo 7 Large collapsed pipe within alignment of moor drain (grip, arrowed)

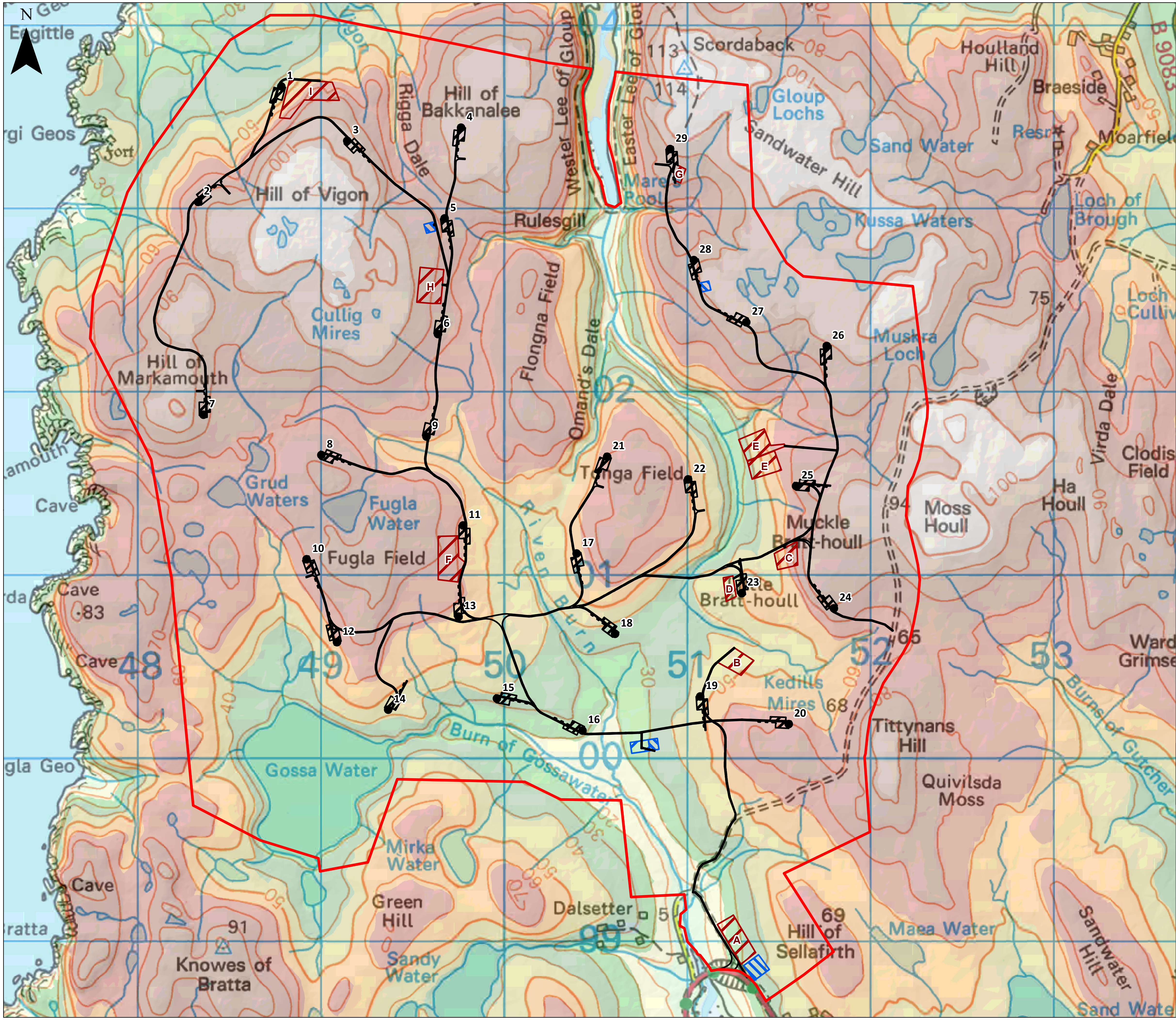
Photo 8 Significant under-cutting of streamside peat deposits by fluvial erosion (on Burn of Kedillsmires)


Photo 9 Eroding peat caused by fluvial incision (below Little Bratt-houll)


Photo 10 Minor crescentic scarp, possibly old gully head (below Muckle Bratt-houll)


Photo 11 Tiers of tension on cracks (arrowed) associated with minor creep / ground displacement

FIGURES



Project Number: 11075

© Crown copyright and database rights 2019. Ordnance Survey 0100031673

Energy Isles Wind Farm
Peat Landslide Hazard and Risk Assessment

Figure 1

Elevation

Date:	Drawn by:	Checked by:	Version:
09/04/2019	AJM	DR	V1